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A Risk-based Approach to Reduction of Warm Air Infiltration for Energy Efficiency Optimization in a Cold Storage System-A Case Study of a Fruit Packaging Plant

Peter Kibagendi Mokaya[1,*], James Wakiru[1], Josephat Tanui[1]

[1] Dedan Kimathi University of Technology, Nyeri, Kenya; peter5kibagendi@gmail.com; james.wakiru@dkut.ac.ke; josephat.tanui@dkut.ac.ke.

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Abstract

Warm air infiltration is a hidden phenomenon that can go unnoticed for weeks, months, or even years in cold storage envelopes. It is a common source of energy wastage that can be explored to achieve significant energy and cost savings. This research assesses warm air infiltration into fruit cold storages using a case study approach for an international fruit exporter based in Kenya, covering baseline study, root cause analysis, and developing a risk-based mitigation strategy to minimize the infiltration rates. Thermal graphic measurements, electricity bills, and on-site observation of the operation patterns provided source data. An Ishikawa diagram and a risk-based Failure Mode and Effect Analysis (FMEA) were used to identify and prioritize root causes, respectively, and a modified decision tree was then utilized to structure the mitigation strategy. The study established a lack of awareness of cold storage operations, irregular and untimed maintenance of components, broken door seals, and inconsistency in the frequency of cold storage door openings as the critical root causes for the warm air-infiltration challenge. It was further revealed that cold storage facilities need to take advantage of the available sensory and operational data to introduce maintenance management systems, temperature-airflow monitoring systems, and environmental control devices to complement the functionality of cold storage components. To operate fruit cold storages optimally and efficiently, facilities management must comprehensively understand the sources of temperature variations and adopt mitigation strategies that minimize warm air infiltration. There is no one-size-fits-all approach to reducing warm air infiltration; thus, both systemic and behavioral approaches must be adopted and integrated into cold storage operations.

Keywords: Warm air infiltration, Energy efficiency optimization, Root cause analysis, Failure identification and prioritization, Mitigation strategy.

1 | Introduction

The agricultural sector is the foundation of most economies worldwide, underpinning its vitality and resilience. Its significance to national economies is irrefutable, constituting an indispensable cornerstone for

Corresponding Author: peter5kibagendi@gmail.com
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socio-economic development. With a steadfast commitment to fostering sustainable development goals, agriculture emerges as a prime source of livelihood through a 'green employment' agenda aimed at alleviating poverty and promoting inclusive growth [1]. It is a baseline for industrial innovation and technological advancements that streamlines business and production processes, optimizes operational efficiencies and enhances productivity. Additionally, agro-processing is a notable contributor to curtailing trade deficits and bolstering self-sufficiency by reducing overreliance on imports. It is a pivotal and significant member in championing environmental sustainability by providing goods and services that foster 'green, clean economy' goals. Nations like Kenya prioritize agro-processing to serve essential public and private purposes, especially in promoting food security [2].

On the contrary, agro-processing is an energy-intensive endeavour comprising numerous divergent significant energy users dependent on the type of processing undertaken. These significant energy users include refrigeration systems that have the potential to realize more than 15% energy savings with minimal capital investment [3]. The associated utility bills are attributable to the slow growth of agro-processing Small and Midsize Enterprises (SMEs) in Kenya. Utility bills, especially energy bills, can be hefty to SMEs to the extent of increasing production costs, making the resultant product uncompetitive, reducing productivity, and lowering profit margins. The common causes of high energy bills in facilities include process inefficiencies, non-optimized production schedules, human factors, and lack of proper energy management systems and practices. Therefore, for such SMEs to remain sustainable in the long run, it is worth maximizing principles of traceability in the identification of the major significant energy users that can be tapped to ensure that the cumulative energy costs are kept low, as well as develop measures to improve the efficiency of energy use.

The case study facility is an agro-processing plant that processes fruits, mangoes and avocadoes for the export market. The facility's main production processes are fruit washing, sorting, drying, packaging, storage, and avocado oil extraction. The facility's fruit processing and avocado oil extraction have enormous energy demands, especially in virgin and crude oil extraction and cold storage of packaged fruits awaiting dispatch. The facility has five significant energy users: electrical appliances, motors, cold storage refrigeration, lighting, and air conditioning systems. The electrical motors and refrigeration systems are the major energy-intensive equipment, representing over 80% of the energy consumed at the facility. Cold storage forms the highest contributor to the electrical load, accounting for 41% of the total electrical load, thus creating a potential avenue to explore in terms of energy conservation. This evidence is in tandem with the findings of Cárcel-Carrasco et al. [4] that cooling systems in production setup can account for up to 44.1% of a facility's total electrical energy consumption. The specificities of the refrigeration systems are provided in *Table A1*.

Process variations within cold storage directly influence the working cycle of refrigerant systems. Regular temperature deviations from the norm due to warm air infiltration cause short cycling, significantly reducing the optimal performance of indoor units and extreme overutilization of supplying compressors, thus compromising their lifespan [4]. For the case study facility, the short-term effect is a heightened energy consumption estimated to have a sensible cooling load of about 698,793.42 kJ, equivalent to an additional 194.12 kWh per day, resulting in elevated electricity bills projected to be upward of Ksh 1.7 million annually from the refrigeration systems alone based on a calculated consolidated energy cost of 25.31 Ksh/kWh as provided in *Tabe A2*. The long-term effect is a drastic reduction of the lifespan of the compressors supplying the cold storges from the recommended 15 years to approximately 5-8 years. These baseline findings suggest that, in general, it is worth prolonging the lifespan of its compressors to ensure they serve their recommended lifetime while minimizing production costs, increasing product competitiveness, and sustaining resultant profit margins. In addition, it is essential to understand the root causes of temperature variations in cold storage that have the potential to cause short cycling on the operation of refrigerant systems for better process control and process improvement [5].

Research on the subject has been mostly restricted to identifying the sources of warm-air infiltration. Surprisingly, identifying critical root causes of the warm-air infiltration has not been closely examined, which could plausibly enhance the identification of more strategic and appropriate mitigation strategies. Despite the

importance of warm air infiltration causes, there remains a lack of evidence on the systematic framework for identifying the critical root causes and deriving appropriate mitigation strategies. In addition, much of the research has adopted either qualitative [6] or quantitative [7], [8] approaches. However, such approaches have failed to address qualitative and quantitative aspects simultaneously, like a hybrid approach. Despite the hybrid approach retaining potential benefits like comprehensively exploring responses and easing the translation of data insights, no previous published research has been reported. Drawing upon the two strands of research into warm air infiltration in cold storage rooms, this study attempts to employ a hybrid approach to identify critical root causes and derive respective and plausible mitigation strategies.

The remaining part of the paper proceeds as follows. Section 2 presents a brief literature review of relevant studies, while Section 3 describes the methodology used for this study. Section 4 presents the results with a brief discussion, whereas Section 5 summarizes managerial implications. Finally, Section 6 covers the proposed recommendations, and Section 7 contains concluding remarks and the proposed future work.

2 | Relevant Literature Review

2.1 | Refrigeration Systems Energy-based Challenges

Refrigeration systems form the common cutting denominator for various agro-processing facilities. Its importance in fostering product quality and prolonging product shelf life cannot be underestimated; however, it comes at an expense, i.e., the massive amount of energy consumed and the associated energy costs [9], [10]. The high costs involved in maintaining low temperatures within cooling chambers demand good efficiency in keeping the cold storage temperatures within the recommended temperature range [10]. This increases the cooling load on the refrigeration system, leading to prolonged periods of operation to maintain the desired low temperatures, hence increasing energy consumption and wear and tear on the system. Counteractively, suitable air flow rates and temperature combinations coupled with an understanding of potential hotspots and recirculation zones would potentially reduce the resultant cooling load. Therefore, it is necessary to advance the optimal performance of cooling chambers to reduce cooling costs and enhance the cooling efficiency of refrigerant systems [11].

2.2 | Warm Air Infiltration

Cold storages constitute cold air creation systems and ventilation systems. Cold storages require maintenance of low temperatures within the required range. However, sustaining consistently low temperatures is an uphill task due to different contributing factors, including warm air infiltration, especially through doorways and edges that disrupt optimal operation patterns of cold storage systems.

Poor edge insulation on the cold storage envelope is an attributable source of infiltration. It creates thermal bridges on the joints, corners, and edges where there is broken and interrupted insulation, leading to warm air leaks through gapings and cracks at the periphery of the stores. In turn, the warm air leaks result in temperature fluctuations within the cold storage that would be detrimental to temperature-sensitive products.

Entrance and exit doorways are essential in loading and unloading cold storage for packaged finished products ready for shipment. The doorways form an air-penetrable interface between the inside and outside environment of the cold storage. Frequent opening of the doorways results in warm air infiltration into the cold storage due to air density differences between air masses in the internal and external environments of the cold stores [8]. Infiltration of warm air into cold storage is problematic to production managers as it increases the operating costs of the refrigerant systems [10]. Additionally, the contact between cold air and ambient air at the doorways can result in mist formation. The vision limitation associated with the mist is an added challenge as it obstructs and impairs the range of vision of the operators loading and unloading the cold storage.

2.3 | Warm Air Infiltration Diagnosis

Different techniques have been used to detect and analyze warm air infiltration, including tracer gas techniques and thermal imaging. The tracer gas technique is costly as it requires expensive equipment with sophisticated technology and a skilled workforce [12]. Thermal analysis is widely used to overcome these challenges [13].

Thermal analysis is performed through the use of infrared (IR) imaging technology. IR imaging is an advantageous inspection technique that relies on non-destructive testing of structural components. IR imaging detects leakages in areas and points where energy is lost from an enclosed element, gathers real-time data to clarify operating conditions for HVAC systems, and identifies heat-related challenges on electrical and mechanical systems when under full-load operation [14].

The IR imaging collects data-based electromagnetic radiations from a system element under inspection, rendering a temperature-thermal image to identify probable hitches. This charts the path to the valuation of possible energy savings, scheduling potential corrective action, and establishing precedence for preventive and predictive maintenance to minimize failure risks [15]. Thermal analysis is essential in establishing the level of edge insulation against the infiltration of warm air from the surroundings.

Thermal imaging has been applied to detect cold air leakage in cold storage. Thermographic images through a thermal imaging system, i.e., a thermal camera, have previously been utilized to identify sources of cold air leakages from a cold room [8]. The study identified that cold air is lost from cold storage due to poor insulation and improper maintenance of the cold chamber. The researchers further image-processed the thermographic images to develop analyzed thermal patterns to detect the exact cold air leakage zones to minimize energy losses within cold storage.

Thermal imaging can be used to crosscheck and evaluate the edge insulation of fruit cold storage through spatial temperature distribution. Thermal camera images have been used to identify insulation problems for the apple fruit cold storage [16]. The study determined insulation issues around the sliding door's connecting areas. The thermal images provided the heat leakage points and were used to identify prevalent hot zones. At the same time, the temperature values extracted were utilized to quantify heat transmission rates over the edges for the respective cold storages. It is from the calculated transmission heat that the optimal insulation thickness of the cold storage was established.

2.4 | Root Cause Analysis

Root Cause Analysis (RCA) lies at the epicentre of identifying critical causal factors for repeated failures. The ultimate goal of RCA is to unearth the root cause of a problem, understand the mitigation approach to undertake, and apply the discoveries to prevent a future repeat of similar causes. RCA is essential in criticality analysis and paves the way for aiming at the right target to eliminate or minimize a recurrent problem. In this study, RCA starts the problem-solving process of minimization of warm air infiltration into fruit cold storage. RCA will identify the critical cause and determine the most appropriate approach to use in implementing a solution. Numerous RCA analysis tools are available depending on the circumstances and situations at hand. RCA tools can be qualitative or quantitative. The RCA techniques available include, but are not limited to, Ishikawa Diagram and Failure Mode and Effect Analysis (FMEA).

2.4.1 | Ishikawa diagram

Ishikawa diagram is a qualitative RCA tool that categorizes potential causes into groupings that branch off the original problem to visualize the cause and effects of a problem. The fishbone diagram groupings are man/mind power (personnel, skills, and knowledge work), materials (consumables and information), machine (equipment and technology), measurements (inspection), method (process), and environment (workplace and surrounding). Possible causes and sub-causes of a problem are identified by following and questioning each of the branched paths until the right cause is singled out [15]. It eliminates unrelated causes and identifies

correlated factors and potential root causes. Ramli and Hamid [6] used an Ishikawa diagram to identify the most energy-intensive equipment for a regional water waste treatment plant. The study identified blowers and aerators as the most significant energy consumers. The cause and effect diagram was essential in allowing the study team to focus on the root cause of the problem rather than its failure history and symptoms. However, the study could not establish a correlation between the other identified causes contributing to high energy consumption within the wastewater plant.

2.4.2 | FMEA

FMEA is a quantitative RCA tool commonly used to explore and rank potential failures in a system. It considers possible failures, consequences, and causes and presents control measures to mitigate each identified failure and severity, occurrence, and detection ratings to evaluate Risk Priority Numbers (RPNs) to dictate advance action [15]. Different studies have utilized FMEA as a quantitative criterion in criticality analysis to identify critical root causes. Bavarsad et al. [13] applied FMEA in identifying risk ranks for perishable goods at cold chains in a port facility. The RPN calculated provided a means to establish the critical areas where perishability risks were at critical levels. Hence, the contributors to trade barriers for perishable products at the port are unearthed. Other unrelated studies that used FMEA in identifying and prioritizing failure modes and proved essential in this study include Wakiru et al. [16] and Vala et al. [17] in prioritizing failure modes in thermal power plants and hospital facilities, respectively. Despite FMEA being a reliable tool in quantifying failure modes, it has a notable limitation. FMEA considers the independent contribution of each failure mode, disregarding the relationship between different failure modes.

2.5 | Mitigation Strategies

A mitigation strategy refers to an action taken to reduce the effects of a risk caused by a hazard. A mitigation strategy involves taking necessary steps to minimize adverse effects or systematically reduce exposure to risk and the likelihood of a risk occurrence [18]. Risk mitigation comprises developing mitigation strategies or plans to manage, eliminate, and reduce risks to acceptable levels. Risk mitigation can take different handling options to determine the most suitable approach in developing a mitigation strategy to act as a checklist for foreseen risks, including acceptance, avoidance, control, transference, and monitoring.

Developing a mitigation strategy to reduce warm air infiltration into cold storage takes a similar approach to a maintenance strategy. It takes either a cost-based or risk-based approach. The cost-based approach is a modified risk-based approach focusing on the costs of various failure modes.

A great deal of previous research into mitigation strategies has focused on risk prioritization, expounding on strategies that account for failure costs, occurrence rates of failures, and effects of failures on plant productivity. Wakiru et al. [16] utilized a risk-based approach with a cost-based FMEA in identifying critical failure modes in selecting risk-mitigating maintenance strategies for a thermal plant. This study considered the type of failure mode, subjecting it to a criticality ranking that was used to determine the plant's maintenance strategy. A decision scheme was developed based on the criticality rank, failure mode deterioration with time, detectable failure mode, and possible modifications. It resulted in a selection scheme for six maintenance strategies, i.e., Failure-Based Maintenance (FBM), Time-Based Maintenance (TBM), Condition-Based Maintenance (CBM), design out maintenance, design for maintenance, and design out reliability.

Drawing from the works of Vala et al. [17], the study used a risk-based approach in selecting operational and maintenance strategies through systematic identification, analysis, and prioritization of recurrent failure modes to promote the availability of specialized medical equipment for a regional hospital facility. The study adopted FMEA in failure frequency analysis and failure modes prioritization in RCA based on lost patient time. It formulated operational and maintenance protocols for selecting appropriate maintenance strategies depending on the identified prevalent failure modes, i.e., human errors.

Collectively, an important overarching theme emerges from the studies reviewed, i.e., mitigation strategies are based on the level of risk exposure and the expected failure costs to assist key decision-makers in prioritizing system and component failures. The use of the risk-based or cost-based approach is dependent on the identified failure modes. Since there is a pool of mitigation strategies, a modified decision tree is deemed an appropriate tool for guiding decision-makers when a failure mode occurs. A modified decision tree considers all potential outcomes and accords a traceable path to a given conclusion. It creates an inclusive assessment of the impact of each decision branch and singles out decision nodes that may require additional examination.

2.6 | Critical Analysis

In view of the different studies reviewed, it was realized that these studies had deficiencies that spurred the drive to pursue this research. The notable deficiencies identified are:

– *Despite several studies using a qualitative approach, such as Ramli and Hamid* [6]*, and others using a quantitative approach, such as Akdemir* [7] *and Pathmanaban et al.* [8]*, the author did not find a cold storage-related study that utilized a hybrid approach. A hybrid approach comprehensively explores responses and eases the translation of data insights. It draws benefits from both qualitative and quantitative approaches. The qualitative approach expounds on the breadth of research, answering questions to what extent and how often. In contrast, the quantitative approach expounds on the depth of research, answering questions on why and how.*

– *Various previous studies that have researched on cold storage, including Akdemir* [7]*, Pathmanaban et al.* [8]*, and Alves et al.* [19]*, tended to focus on identifying sources of warm air infiltration rather than identifying and prioritizing critical root causes. This study goes beyond identification to prioritize critical root causes and align the mitigation strategies to critical failure modes. Additionally, in the reviewed related studies mentioned above, there was no systematic methodology for RCA and in developing and selecting mitigation strategies. An additional aspect this study sought to address.*

This study aimed at devising an optimization approach to energy usage in cold storages. A hybrid approach anchored on the Ishikawa diagram and a risk-based FMEA investigates the root causes contributing to high rates of warm air infiltration into fruit cold storages and utilizes a systematic methodology in structuring strategies to mitigate the critical root causes.

3 | Methodology

The methodology followed a sequential risk management framework in establishing context, risk assessment, and risk treatment as per guidelines and principles set out in ISO 31000:2018. It was ensured that the methodology aligned with the standard framework at the process level, i.e., the problem identification corresponded with establishing context, RCA conformed with risk identification, analysis, and evaluation, and the structuring of the mitigation strategy was consistent with risk treatment [20]. A baseline study was conducted in the cold storages during the problem identification phase, the Ishikawa diagram and FMEA were used in RCA, and a modified decision tree was utilized for organizing the mitigation strategy. *Fig. 1* provides an overview of the methodology adopted during this study.

3.1 | Data Collection

The research study used both primary and secondary data. The primary data sources were thermal measurements and on-site observation of the operation patterns of the cold storage. Sample thermal graphic images captured at the facility are provided in *Fig. A1*. On-site observation of the cold storage's normal operations was conducted to understand the routine operational undertakings of the case study facility. The secondary data sources used were the utility electricity bills obtained from the accounts department of the facility and previously published literature on similar studies.

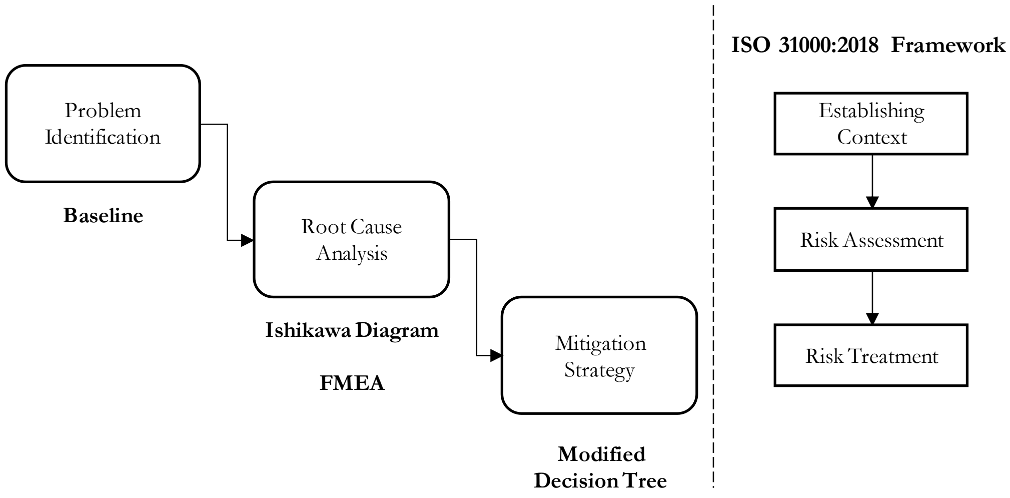

Fig. 1. Methodology overview.

3.2 | Baseline Study-Thermal Imaging

The study adopted a case study approach. In establishing the baseline context, an array of investigations were undertaken on refrigeration systems at the case study facility, including performance evaluation of both indoor and outdoor units to establish respective coefficients of performance, temperature deviation tests, and effects of warm air infiltration into the cold storage with the doorway as the interface in addition to the recommended insulation effectiveness, air tightness, and refrigeration capacity tests [21]. Other factors were within the limit. However, the temperature deviations were significant, especially at the doorways. With the help of a thermal imaging camera, it was established that the cold storage still experienced excessive warm air infiltration even when doors were closed. A significant temperature deviation prominent between the maximum temperature within the cold storages and the preset operating temperature of 5±2°C was noted. This led to energy wastage as the supplying compressors had to run extra time to maintain the preset temperature of the cold storage [9].

A worksheet centred on the thermal images captured was used to analyze the present state of the refrigeration systems for the facility's cold storage. During the thermal analysis of the present state, the worksheet proved vital in establishing the rates of warm air infiltration, the volume of warm air infiltration, the heat gain within the cold storage due to warm air infiltration, and in determining potential energy savings. Additionally, it came in handy when analyzing the facility's electricity bills and determining its consolidated electricity costs.

An empirical model based on Tamm's equation, provided in *Eq. (1)*, was used in the worksheet to predict the infiltration rates through doorways into the cold storage.

$$\mathrm{Q_{Tamm}} = 0.67\mathrm{WH}\sqrt{\frac{2\mathrm{gH}(1-\mathrm{s})}{\left(1+\mathrm{s}^{\frac{1}{3}}\right)^{3}}}, \tag{1}$$

where Q_{Tamm} is air infiltration rate (m3/s), W is the door width (m), H is door height (m), g is the gravitational acceleration (m/s2), s is the ratio of warm air density to cold air density (ρ_{out}/ρ_{in}), ρ_{out} is the density of air outside the door (kg/m3), and ρ_{in} is the density of air on the inner side of the door (kg/m3).

3.3 | Root Cause Analysis

An Ishikawa Diagram was utilized for qualitative analysis, while an FMEA was used for quantitative analysis of the root causes. The Ishikawa Diagram was treated as the key tool for root cause determination, whereas the FMEA was critical in prioritizing failure modes. The Ishikawa Diagram categories explored were measurement, materials, methods, workforce, environment, and machine [6]. This was followed by identifying

possible causes under each category through a brainstorming session with the production team. The causes were further broken down into sub-causes to determine the significant area of focus [15].

The study utilized FMEA to analyze the causes and prolonged effect of warm air infiltration, resultant failures, and the bound consequences of each consequent failure. The three critical aspects captured in the FMEA were the failure modes, causes, and effects [22]. Risk prioritization was applied to evaluate potential failures, with the prioritization parameters acting as the input factors for the FMEA. The risk prioritization parameters considered were the likelihood of risk occurrence, the severity of the risk effect, the risk detection factor, and the RPN [15]. The likelihood of occurrence was regarded as the chance of a failure cause happening, the severity was deemed as the impact of the accompanying consequences in the event a failure risk occurring, and the risk detection factor was considered as the ability to detect the failure risk early enough to take action immediately. The baseline RPN equation used was [13], [15–17];

$$\text{RPN} = \text{Likelihood of Risk Occurrence} * \text{Severity of Risk Effect} * \text{Risk Detection Factor}. \tag{2}$$

The Ishikawa diagram and FMEA were deemed suitable for this study as they eliminate unrelated causes and identify correlated factors and potential root causes. A modified decision tree was employed in structuring the mitigation strategy as it considers all potential outcomes and accords a traceable path to a given conclusion.

3.4 | Development of Mitigation Strategies

The structuring of the mitigation strategy to reduce warm air infiltration into the cold storages took a similar approach to that of a maintenance strategy with the intent to curb the prioritized recurrent failure modes. The approach adopted was comparable to that of Wakiru et al. [16]. It is considered the ultimate step-by-step route to minimize adverse effects and systematically reduce exposure to warm air infiltration risk and the likelihood of the risk occurrence [18]. The mitigation strategy utilized a modified decision tree to select an appropriate mitigation approach based on a selection criterion. The alternative mitigation strategies considered were reactive, preventive, predictive, or redesigned.

4 | Results and Analysis

4.1 | Baseline Study Results

Based on the baseline approach in Section 3.2, the warm air infiltration rates into the cold storages and resultant heat gain were evaluated. *Table 1* shows the estimated infiltration rates and the heat gains due to warm air infiltration from the different cold storages at the facility. The evaluation was based on thermo-graphic images captured at the facility using a thermal imaging camera. It was assumed that the daily cold storage door opening would amount to around one and a half hours, and the ambient temperature was taken as 22°C. It was noted the rates of warm air infiltration were above 1 m^3/s for all the five active cold storages under study. The cumulative daily heat gain amounted to 698,793 kJ, equivalent to 194.1 kWh per day. The extrapolated temperatures and densities from the thermal graphic images are provided in *Table A3*.

In the next section, the paper identifies root causes and prioritizes the critical root causes.

Table 1. Estimated infiltration rate and heat gains in different cold storage.

Parameter	Units	Precold Storage 1	Precold Storage 2	Precold Storage 3	Precold Storage 4	Dispatch Cold Storage 1
Door width, W	m	1.9	1.9	1.9	1.9	1.8
Door height, H	m	2.7	2.7	2.7	2.7	2.7
Gravitational acceleration, g	m/s^2	9.81	9.81	9.81	9.81	9.81
The density of air outside the door, ϱout	kg/m^3	1.191	1.195	1.197	1.209	1.188
The density of the air inside the door, ϱin	kg/m^3	1.253	1.256	1.256	1.240	1.221
The ratio of warm air density to cold air density, s, $\varrho_{out}/\varrho_{in}$		0.9499	0.9510	0.9529	0.9752	0.9729
Ambient temperature	°C	22	22	22	22	22
Approx. daily door opening time	Hrs	1.5	1.5	1.5	1.5	1.5
Air infiltration	m^3/s	2.0053	1.9826	1.9424	1.4014	1.3888
The volume of air infiltration per day	m^3	10,828.58	10,705.96	10,488.90	7,567.42	7,499.52
Density of air at ambient temperature	kg/m^3	1.1960	1.1960	1.1960	1.1960	1.1960
Average air specific heat capacity, Cp	KJ/kg	1.007	1.007	1.007	1.007	1.007
Temperature difference, t		15	15	14	7	8
Heat gain per day, Q	KJ	195,102.89	187,735.96	176,350.23	66,714.42	72,889.91
	kWh	54.195	52.149	48.986	18.532	20.247
Compressor power rating	kW	16.00	16.00	16.00	16.00	12.00
Compressor cooling capacity	kW	39.45	39.45	39.45	39.45	28.60
Coefficient of performance, CoP	unit	2.465625	2.465625	2.465625	2.465625	2.383
No. of doors per cold room	#	1	1	1	1	2

4.2 | Root Cause Analysis

After conducting multiple walkthroughs, observing operation patterns, and interviewing work floor production personnel on-site at the case study facility, a cause-and-effect diagram and FMEA were developed. These analytical tools were instrumental in identifying and assessing the critical root causes contributing to the elevated levels of warm air infiltration. The thorough investigation targeted providing comprehensive insights into the underlying factors influencing the observed phenomenon.

The Ishikawa diagram considered the six main categories: method, materials, measurement, environment, workforce, and machine. The categories were populated based on the factors identified as significant and pivotal contributors to the prevalent issue of high rates of warm air infiltration into cold storage. The factors were analyzed and incorporated into the cause-and-effect diagram to represent the root causes visually. *Fig. 2* illustrates the developed Ishikawa diagram, showcasing the interconnected factors contributing to warm air infiltration.

The frequently appearing root causes in the Ishikawa diagram were identified as significant causes and input into the FMEA. Subsequently, the FMEA was conducted with the primary target to evaluate the RPN. *Table 2* presents a sample outcome of the FMEA analysis. The RPN was determined using *Eq. (2)*. From this assessment, the top three failure causes, as per RPN ranking, emerged as critical root causes. The ranking criteria for the critical root causes were based on the ranking criteria adopted in studies by Wakiru et al. [16] and Vala et al. [17]. The RCA findings underscore the significant contribution to the heightened incidence of warm air infiltration within the cold storage facilities.

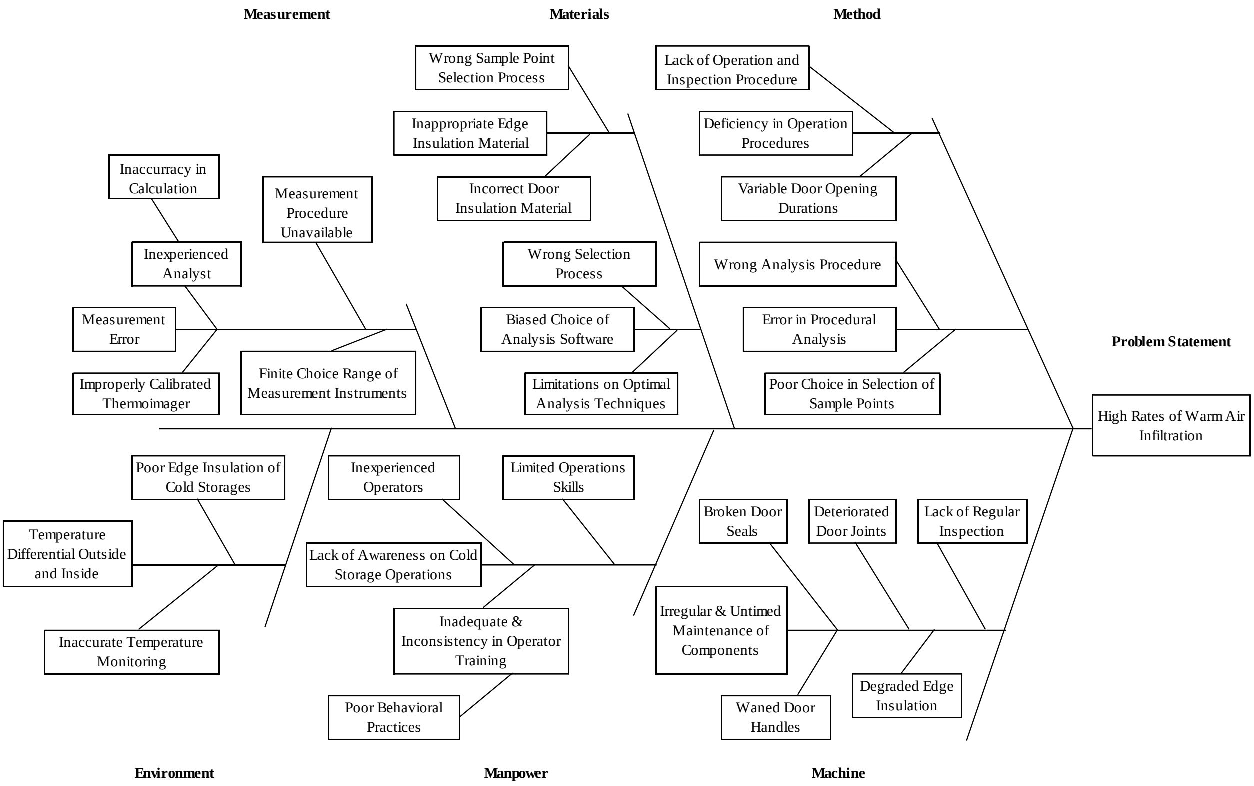

Fig. 2. Causes and effect diagram for warm air infiltration.

The FMEA revealed an inadequate understanding of cold storage operations, broken door seals, irregular and untimed maintenance of cold storage components, and erratic door opening frequencies as the critical root causes. Conversely, poor operational behaviours and experiences of cold storage operators, along with causes like waned door handles and deteriorating door joints, fell within acceptable thresholds and were thus considered manageable. Notably, the insulation along the cold storage edges was effective, hence making a negligible contribution to warm air infiltration.

The RCA findings aligned with five notable cardinal pillars: hot spots for warm air infiltration, concerns over maintenance timings, compromise on performance reliability, limited knowhow on procedural undertakings for operators, and prolonged operation time and short-cycling effect on compressors supplying the refrigerated systems.

In the next section, the paper derives the mitigation strategies of the critical root causes.

Table 2. Sample FMEA analysis for the root cause of warm air infiltration.

Failure Mode	Failure Causes	Likelihood of Occurrence (1-10)	Likelihood of Detection (1-10)	Severity (1-10)	Risk Priority Number (O*D*S)	Rank	Action to Reduce Occurrence of Failure
High rates of warm air infiltration	Broken door seals	9	8	9	648	2	Routine checks and periodic maintenance of components Introduction of environmental control devices to complement the functionality of cold storage components
	Deteriorated door joints	9	7	9	567	4	
	Poor edge insulation	5	3	9	135	7	
	Waned door handles	8	9	7	504	5	
	Irregular and untimed maintenance of cold storage components	9	8	9	648	2	Timely planning of maintenance actions
	Inexperienced operators	8	7	8	448	6	Training of operators and conducting refresher training periodically
	Poor behavioral practices	8	7	9	504	5	
	Inadequate and inconsistency in operator training	8	8	9	576	3	
	Lack of awareness of cold storage operations	9	9	9	729	1	Creating and updating cold storage operation guides and conducting refresher training
	Inconsistency in the duration of door opening and closing	8	9	9	648	2	

4.3 | Mitigation Strategy

The mitigation strategy for addressing warm air infiltration into the cold storage considered two primary fundamental factors: the current state of cold storage components and the available sensory information regarding temperature and airflow. *Fig. 3* depicts the decision tree for deriving the mitigation strategies and actions.

If the infiltration risk rate is low, the facility can continue to operate the cold storage normally while prioritizing FBM on non-critical components susceptible to high failure rates, such as door seals, handles, and joints. In circumstances where the severity of infiltration increases with time, the operations team should prioritize TBM on critical components that are in constant usage by planning ahead of time to carry out periodic repairs and servicing.

For instances where infiltration is random, taking advantage of an online monitoring system with sensory data points and deviation alarm notifications is essential. Detection-Based Maintenance (DBM) is recommended for such scenarios, which involves crosschecking the temperature-airflow distribution within the cold storage.

If the temperature-airflow combination exceeds the levels recommended by the Original Equipment Manufacturer (OEM), then Design-Out Maintenance (DOM) is proposed, especially where minor component modifications are needed. Otherwise, the random nature of infiltration can be attributed to the behavioural practices of the operators, and thus, refresher training to enhance awareness of operation guidelines and procedures is proposed.

In scenarios where a facility lacks an online monitoring system, an offline system with historical performance records of components can be used, and priority should be directed towards CBM to ascertain the remaining useful life of the cold storage components. In situations where the prevalence rate of the infiltration is constantly increasing to the extent of requiring eradication, a facility can opt to redesign the entire cold storage system while prioritizing Design-Out Reliability (DOR) to retain the maintainability aspect of the cold subsystems.

In all instances, the operations team must diligently maintain an integrated framework incorporating regular inspections of critical components. Moreover, sufficient spare parts stock should be maintained to ensure optimal operational efficiency and minimal downtime disruptions.

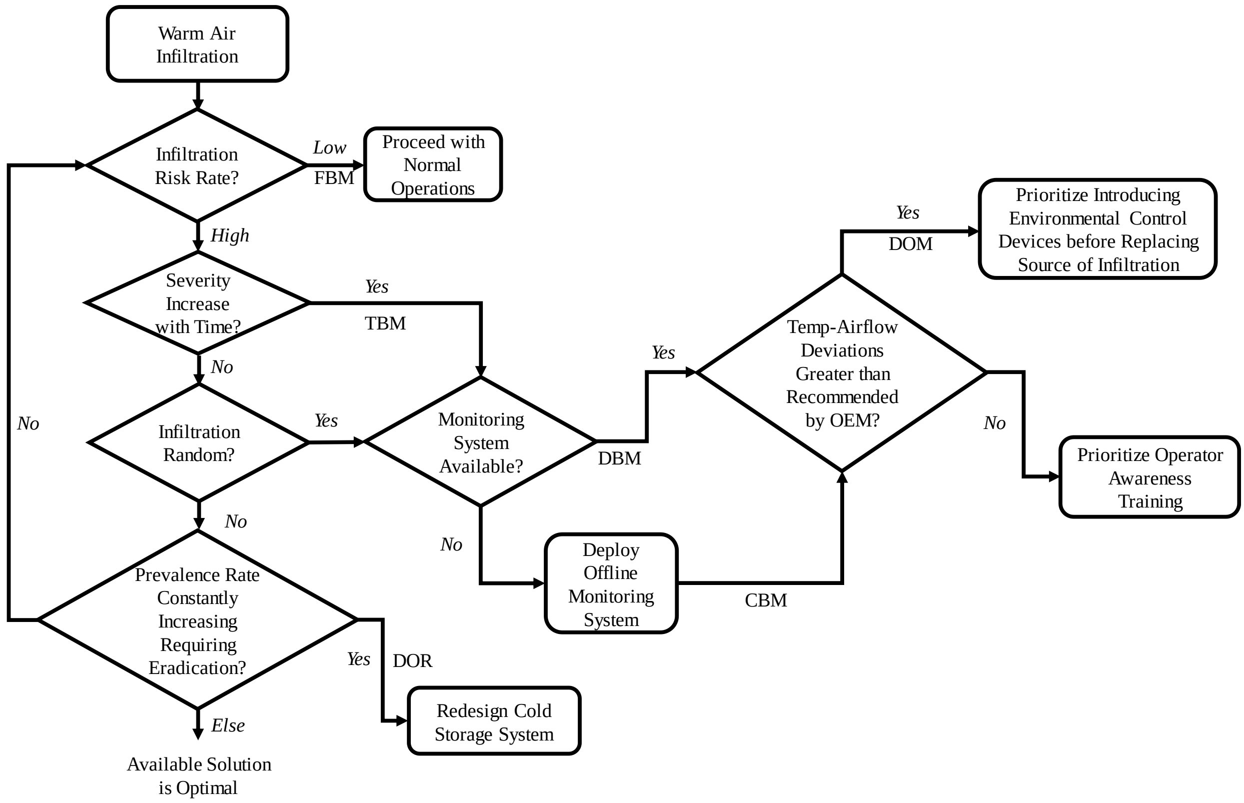

Fig. 3. Decision tree for deriving mitigation strategy.

As an illustration, the top critical root cause for our case study facility was a lack of awareness of cold storage operations on the operators' end. A lack of awareness signifies that the infiltration risk rate is high, and its severity is bound to increase with time due to operator negligence unless action is undertaken. Thus, the facility should not proceed with normal operations. Since the operators are unaware that their behavioural operation patterns impact warm air infiltration, the door opening/closing frequency will be irregular, resulting in a randomized nature of infiltration. Our case study facility lacks an online monitoring system. Therefore, we must rely on an offline monitoring system and, hence, settle on CBM action subject to the available operation, maintenance, and repair records at the facility to gauge the remaining useful life of cold storage components. However, since the heightened energy consumption is operator-based, we can perform instrument measurements on the temperature-airflow deviations and compare them against the combinations recommended by the OEM. If the deviations are minute or negligible, the facility management should focus on refresher training on cold storage operation procedures. If the deviations are significant, we can explore

the possibility of introducing environmental control devices, such as air curtains, before we assess the option of replacing the infiltration source, i.e., the door.

A summary of the identified critical root causes and the respective mitigation strategies for the case study facility is provided in *Table 3*.

Table 3. Root cause and respective mitigation strategy.

Critical Root Cause	Mitigation Strategy
Lack of awareness of cold storage operations	Prioritize operators' awareness training.
Inconsistency in the duration of door opening and closing	
Irregular and untimed maintenance of cold storage components	Prioritize proactive maintenance strategies
Broken door seals	Prioritize introducing environmental control devices before replacing the source of infiltration.

5 | Managerial Implications

Assessing the current state of cold storage components involves comparing their condition to historical performance to determine the remaining useful lifetime. Various components are to be inspected, including checking for broken door seals, evaluating deterioration of door joints, assessing the level of wear on door handles, and examining the overall condition of edge insulation. Facilities lacking a maintenance tracking system, such as our case study facility, would benefit from implementing a Computerized Maintenance Management System (CMMS). A CMMS streamlines maintenance operations and tasks, tracks component performance history, stores maintenance data, provides real-time work activity reports and schedules preventive maintenance tailored for different cold storage components. Adhering to effective operation and maintenance practices for energy-consuming systems minimizes energy wastage and enhances efficiency along the production line.

Sensory information plays a crucial role in identifying significant deviations in temperature and airflow from an ideal operating conditions perspective. The available data on cold storage relies on factors such as facility operation patterns, operators' behavioural practices, consistency in operator training, and adherence to standard operating procedures for cold storage. As a complementary measure to reduce warm air infiltration and promote optimal performance with minimal temperature-airflow fluctuations, cold storage facilities would require environment control devices tailored to accommodate the functionality of cold storage components, existing facility operation patterns, and operators' behavioural practices. These devices may include temperature control and monitoring systems, regular temperature-airflow deviation alerts, and air curtains.

Effective energy management in production lines necessitates a combination of operational excellence and robust maintenance practices. By implementing proactive strategies like those outlined above, similar cold storage facilities would mitigate warm air infiltration, optimize energy consumption, and enhance overall operational efficiency. The seamless integration of these strategies will allow facilities to achieve sustained energy efficiency and operational excellence in their cold storage operations.

6 | Recommendations

Based on the comprehensive analysis conducted on the warm air infiltration baseline, the root causes identified through the Ishikawa diagram and FMEA, and the mitigation strategy developed, the following recommendations are proposed to mitigate the prevalent and recurrent issue:

I. Enhance cold storage operators' training by providing regular refresher operation drill sessions to raise awareness of proper cold storage operation guidelines and behaviours. This can help minimize human-induced factors contributing to warm air infiltration.

II. The facility could consider integrating environment control devices into its building management systems. Install air curtains and temperature-airflow control systems with deviation alerts to manage temperature and airflow effectively. Align and adjust these devices to match the operational patterns of the facility and the behavioural patterns of the operators to ensure optimal performance.

III. Facilities should deploy online monitoring systems to track temperature and airflow distribution within their cold storage. DBM should be incorporated to identify deviations from optimal conditions and trigger necessary repairs or adjustments.

IV. Prioritize proactive maintenance strategies. Facilities should implement maintenance strategies focusing on critical cold storage components that are in constant use, especially the doorway, i.e., the door seals, handles, and joints. Priority should be directed towards FBM and TBM to ensure optimal component performance and prevent unexpected failures, especially where infiltration risk and severity increase with time.

V. Implement a maintenance tracking system. A facility lacking an online monitoring system should adopt a CMMS to track the performance history of critical components, schedule preventive maintenance, and streamline maintenance operations.

7 | Conclusion

This study set out to develop a risk-based approach to reduce warm air infiltration into fruit cold storage systems by exploring the critical root causes contributing to the high infiltration rates and structuring corresponding mitigation strategies. The results of this study show that the primary drivers behind warm air infiltration in cold storage facilities are inadequate understanding of cold storage operations on the operator end, broken door seals, irregular and untimed maintenance of cold storage components, and erratic door opening frequencies. The proposed mitigation strategies represent a proactive approach to maintenance prioritization, utilization of temperature-airflow monitoring systems, enhancing operator training, implementation of maintenance tracking systems, and exploring the feasibility of installing environmental control devices in cold storage systems. The findings of this study provide insights to effectively address issues related to unwanted warm air infiltration, optimize energy usage, and improve the overall operation efficiency of fruit cold stores. Overall, this study strengthens the idea that continuous focus on the proposed strategies is essential to maintain optimal energy efficiency levels and operational excellence in cold chain operations. This can be achieved by incorporating both systemic and behavioural approaches into daily operations to ensure that such facilities have a competitive future in the cold storage industry and achieve long-term sustainability goals. The findings reported in this study have contributed to the existing knowledge on warm air infiltration in cold storage envelopes by shedding light on the use of a hybrid approach in identifying and prioritizing critical root causes and the use of a systematic methodology to develop, select, and align mitigation strategies to critical failure modes.

The study was limited to fruit cold storage with a controlled atmosphere. However, future works can explore other cold stores, including those operating in subzero temperatures, such as refrigerated chilled/frozen warehouses and blast freezers. The present work has laid the groundwork for future research using a similar methodology to explore and investigate other influencing determinants and the possibility of utilizing statistical methods for risk level analysis and categorization in assessing the optimal energy usage in a cold storage system through the infiltration dimension.

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Author Contribution

Conceptualization, P.K. and J.W.; formal analysis, P.K.; investigation, P.K., and J.W.; Methodology, P.K., J.W., and J.T.; data maintenance, P.K.; supervision, J.W. and J.T.; visualization, P.K., J.W., and J.T.; writing-original draft, P.K., J.W., and J.T.; writing-reviewing and editing, P.K., J.W., and J.T. All authors have read and agreed to the published version of the manuscript.

Data Availability

The analysis data used to support the study findings are included in this research article and the appendix and will be available upon request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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